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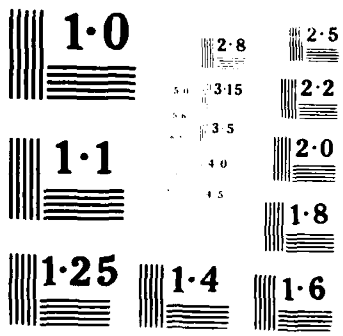
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A systematic approach to the configuration synthesis of robot arms and wrists has been developed. A simple method for representing and analyzing robots, called the zero reference position method, has been developed. The analysis includes forward and inverse kinematics, direct and inverse dynamics, and robust numerical algorithms. A method for approximate manipulation based upon a goal chasing strategy has been developed which is suitable for gross robot motions.

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CONFIGURATION SYNTHESIS AND APPROXIMATE MOTION PROGRAMMING OF ROBOT MANIPULATORS

Final Report

K.C. Gupta

December 10, 1986

U.S. Army Research Office
20125EG/DAAG29-83-K0144

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Forward

This final report for USARO 20125EG/DAAG29-83-K0144, titled "Configuration Synthesis and Approximate Motion Programming of Robot Manipulators," briefly describes the research work done during the period from October 1, 1983 to September 30, 1986. Specific details of the research performed can be found in the published, or soon to be published, technical papers; the Army Research Office has already been provided with the copies of these papers.

Statement of Problems Studied

I. Rationalize the process of synthesizing and ev uating robot arms and wrists.

II. Develop a simple method for representing, and analyzing the kinematics and dynamics of robot manipulators.

III. Develop approximate manipulation strategies for robots which are not computationally intensive.

I. Configuration Synthesis of Robot Arms

Configuration synthesis deals with the rational process of determining geometrical parameters of a robot arm including those of the wrist in order to achieve certain performance characteristics. This research has developed the workspace analysis into a unifying tool for configuration synthesis. This is a departure from the traditional interpretation of the workspace in which only its volumetric aspects are considered to be significant. We have shown[1] that the workspace can be used to determine dexterity, joint solution space, singular surfaces in the workspace, and transformation characteristics of various kinds of empty spaces (holes, central voids, toroidal voids). The condition for optimum dexterity of anthrophomorphic robot structure has been shown to be that the distances bet en the shoulder and elbow, elbow and wrist, and wrist and tool tip be equal.

Robot wrist structures which are kinematically equivalent to spherical wrists are commonly used. The problem of tool spin with respect to various axes passing through the spherical wrist center has been investigated. This problem arises because a tool mount is often used to mount the tool on the end-effector, and simple rotations about the component joint axes of the wrist are not sufficient for many tasks; rather, coordinated joint rotations

[1]K.C. Gupta," On the Nature of Robot Workspace," Israel Journal of Technology 22: 71-79, 1984/5; International Journal of Robotics Research 5(2): 112-121 1986 (revised).

axes passing through the spherical wrist center has been investigated. This problem arises because a tool mount is often used to mount the tool on the end-effector, and simple rotations about the component joint axes of the wrist are not sufficient for many tasks; rather, coordinated joint rotations at the wrist axes must be considered to induce effective rotation of the tool about certain axes passing through the spherical wrist center. But this is not possible in general, and rigorous conditions for the wrist and tool mount parameters have been derived[2] to insure the spin of the tool about certain axes, as well as about arbitrary axes, passing through the wrist center.

II. Zero Reference Position Method

A simplified method for representing and analyzing robots has been developed. This method, called the zero reference position method, can be learned easily. Engineers without an extensive background in advanced kinematics can become proficient in using this method in a short time; this is a very attractive feature because robotic system development is an interdisciplinary activity which draws engineers and scientists from various technical backgrounds. The zero reference position description is in terms of the joint axes directions and locations in a suitably chosen position of the robot where all of the joint variables are defined to have zero values. The governing kinematic equations of the robot are derived from this data by applying an important, but often neglected, principle of displacement similarity. This leads to an explicit and efficient method for kinematic

[2] K.C. Gupta, "Rotatability Considerations for Spherical Four Bar Linkages with Applications to Robot Wrist Design," ASME Journal of Mechanisms, Transmissions, and Automation in Design, 108: 387-391, 1986.

analysis[3]. A quantitative comparison of this method with the implicit and less efficient method of Vukabratovic, Suh, Radcliffe, et. al. has been developed. Engineers who are well versed with the method of Pieper-Roth, which is based upon DH representation, will also appreciate the simplicity and directness of the zero reference position method; at the very least, it can be used as an independent method to verify the complicated derivations of equations.

A small catalog[4] of closed-form solutions using the zero reference position method has been developed. The following list indicates the variety of industrial robots which have been considered.

Cartesian robot with 3 roll wrist[4]

Cylindrical robot with 3 roll wrist[4]

Spherical robot with 3 roll wrist[4]

Stanford Arm[4]

SM 229 robot[4]

PUMA[4]

Bendix robot[3]

Cincinnati-Milacron T3[5]

A recently developed three-roll wrist design is based upon the principle of differential type bevel geared trains. Such a wrist leads to a compact and sturdy wrist design and it also reduces the mass which is far from the base column. Closed-form kinematic solutions for robots with geared three-roll wrists has been developed[4] so that these robots can be controlled by computers.

[3] K.C. Gupta and G.[illegible]. Carlson, "On Certain Aspects of the Zero Reference Position Method and Its Applications to an Industrial Manipulator," Proc. IEEE Conf. Robotics and Automation, 2: 728-733, 1986 (condensed); Journal of Robotic Systems 3(1): [illegible], 1986 (revised).

[4] K.C. Gupta, "Kinematic Analysis of Manipulators Using the Zero Reference Position Description," International Journal of Robotics Research 5(2): 5-13, 1986.

[5] K.C. Gupta, Lecture Notes on Robotics (ME 410 at UIC), 1985.

Closed-form analytical solutions can be derived for most industrial robots. However, iterative techniques are useful when the closed-form solution is not readily available, or a general purpose robot motion analysis software is to be developed for these situations. A robust algorithm for numerical inverse kinematics has been developed[6]. This algorithm exploits some important features of robot kinematics to develop a special variable step predictor-corrector scheme for integrating the velocity equations of the robot. It has been shown to be reliable, stable and efficient. The problems of unpredictable and unexplainable divergence, which plague ordinary numerical schemes for inverse kinematics, have been eliminated. This algorithm can also converge at those positions of the robot which are almost singular--ordinary algorithms for inverse kinematics start misbehaving when joint angles have values within 5°-10° of their singular values. A robust algorithm for numerical inverse kinematics is an important first step in developing a general purpose robot controller. A subsequent modification of this algorithm[7] has improved its time efficiency considerably. This algorithm replaces all rotation matrix related operations with their vector equivalents by using the Euler parameters. Other changes which are considered minor improve the linear equation system solver, the computation of the rotational deviation errors, and the predictor-corrector iteration logic.

The zero reference position method has also been extended to the domain of manipulator dynamics[8]. The additional data concerning the dynamic

[6] K.C. Gupta and K. Kazerounian, "Improved Numerical Solutions of Inverse Kinematics of Robots," Proc. IEEE Conf. Robotics and Automation 743-748, 1985.

[7] K.C. Gupta and V.K. Singh, "A Numerical Algorithm for Solving Robot Inverse Kinematics," Proc. IFToMM World Congress, Spain, 1987 (to appear).

properties of the manipulator is defined in the zero reference position. This includes the body vectors from the joints on a link to the mass center of the link, weights of the links, and the inertia matrices for the links with respected to the translated base coordinate system located at the link centers of masses. For the inverse dynamic problem, the motion of the end-effector and the forces acting on it are known, and we need to compute the joint torques which are needed to drive the manipulator. A recursive Newton-Euler formulation has been developed by considering the equations of dynamic equilibrium for each link. Two key observations are that the forms of the generalized Euler equations in the centroidal body system and the translated base system are similar, although the inertia matrix in the latter case is time varying; and that an appropriate link related transformation of all vector quantities as well as the inertia matrix reduces the number of matrix calculations significantly. The computational complexity analysis of this approach shows that it compares favorably with other approaches for joint force/torque computations.

In manipulator simulation[8], the joint forces/torques are given and the motion of the robot needs to be determined. For this problem, the above mentioned recursive Newton-Euler formulation is appropriately revised to numerically set up the state equations of the manipulator; the state variable vector consists of the joint variable values and the joint velocities. In particular, the coefficients of the governing system of nonlinear and ordinary differential equations are not determined explicitly. Rather, assuming that

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[8] K. Kazerounian and K.C. Gupta, "Manipulator Dynamics Using the Extended Zero Reference Position Description," Proc. 9th Applied Mechanisms Conf. 2: 6.1-6.11, 1985; IEEE Journal of Robotics and Automation 2(4); 221-224, 1986 (revised).

the current state (joint values and velocities) of the manipulator is known, the recursive Newton-Euler equations are manipulated algebraically to calculate the rates of the state variables--this numerical set up is precisely what is needed for the numerical integration of the dynamics equations for which a predictor-corrector method has been used.

III. Approximate Manipulation of Robots

An important requirement for the design of an autonomous robotic system is that it be able to do trajectory planning and perform the related inverse kinematics and inverse dynamics calculations in real-time using a small on-board computer. However, these computations are well beyond the real-time computing capabilities of small computers. Therefore, alternate manipulation strategies must be developed which are not so computationally intensive. This research has developed one approach to this problem. A strategy has been developed which is based upon the idea of the end-effector being attracted by a hypothetical goal which is either stationary[9], or moving along a prescribed trajectory[10]. A three part force-couple system is synthesized to move the end-effector toward the hypothetical goal, to slow down the end-effector if its speed becomes excessive, and to direct it toward the prescribed trajectory if the end-effector tends to drift off course. Further adjustments are necessary to improve the accuracy and to avoid sudden changes in the synthesized force-couple system. A Jacobian transformation is used to convert this force-couple system at the end-effector into the joint torques which are

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[9] K. Kazerounian and K.C. Gupta, "A Target Tracking Manipulation Theory for Robots," Proc. 6th IASTED Symposium on Robotics and Automation, 1985; IASTED Journal of Robotics and Automation 1(3): xxx, 1986 (to appear).

[10] G.J. Carlson and K.C. Gupta, "A Strategy for Approximate Manipulation of Robots," Proc. ASME Computers in Engineering Conf. 1: 87-94, 1986.

required to drive the manipulator; gravity and static payload effects are also compensated. This computation requires only the multiplication of the 6x6 transposed Jacobian matrix with a 6x1 column vector of the end-effector force-couple system; in particular, inversion of Jacobian matrix is not necessary. When this approximate manipulation strategy was evaluated by using numerical simulation, it was found to be reasonably accurate for gross motions of the robot arm.

[illegible] for Spherical [illegible]
[illegible] Robot Wrist Design

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1. K.C. Gupta, "On the Nature of Robot Workspace," Israel J. Tech. 22: 71-79, 1984/5; Intl. J. Rob. Res. 5(2): 112-121, 1986 (revised).

2. K.C. Gupta, "Kinematic Analysis of Manipulators Using the Zero Reference Position Description," Intl. J. Rob. Res., 5(2): 5-13, 1986.

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